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SUMMARY

An experimental study was conducted to determine the behavior of liquid nitrogen and liquid hydrogen in spherical and cylindrical tanks after entering a weightless environment. The results of this study revealed that the configuration of the liquid-vapor interface in spherical tanks for both liquids was a totally wetted tank wall typical of liquids with a 0° contact angle. Also, the configuration of the liquid-vapor interface of nitrogen in a cylindrical tank was a surface of constant curvature with a radius equal to the radius of the cylindrical tank. A determination of the time required for the liquid-vapor interface to reach equilibrium resulted in an extension of the Weber number scaling parameter to include the cryogenic liquids.

INTRODUCTION

The NASA Lewis Research Center is currently conducting a study to determine the behavior of rocket engine propellants stored in space-vehicle tanks while exposed to weightlessness (zero gravity) during coasting periods. In order to solve many of the problems that will be encountered in the design of space vehicles, a knowledge of the zero-gravity equilibrium configuration of the liquid-vapor interface, the time required for the system to reach that equilibrium configuration, and the stability of the system is required. The liquid and vapor could, of course, be positioned by means of acceleration fields such as those produced by spinning the tank or accelerating (collection) rockets, but these methods are active rather than passive systems and require the expenditure of energy. The proper employment of the surface-energy properties of the solid-liquid-vapor system through the use of suitable tank geometry offers the possibility of a passive propellant management system that requires no expenditure of energy.

The configuration of the liquid-vapor interface under weightless conditions has been studied analytically by several investigators. The analysis presented in reference 1 is typical of these studies and indicates that the configuration of the liquid-vapor interface is a function of the contact angle and the geometry of the container. The interface configurations predicted by the analysis have been verified experimentally for a range of wetting and nonwetting liquids with contact angles from 0° to 125° and for several container geometries. The experimental studies were conducted in a zero-gravity drop-tower facility and are presented in references 2 to 5.

The time required for the liquid-vapor interface to reach its zero-gravity equilibrium configuration has been studied by many investigators. In the analyses of references 1 and 6, which are typical of such studies, the time response of a deformed liquid drop (a liquid-vapor system) under the action of capillary forces was analytically determined. Of most interest to the space-vehicle designer, however, are solid-liquid-vapor systems where the zero-gravity equilibrium configuration in the propellant tanks is generally a liquid-wetted tank wall (typical of propellants with a 0° contact angle). The results of a previous experimental study (ref. 7) established a functional dependence of the time for the liquid-vapor interface of several common liquids to reach equilibrium on the pertinent liquid parameters and system dimensions for spherical, cylindrical, and annular tanks. The time to reach equilibrium is herein defined as the time for the first pass of an underdamped system through its steady-state position. The form of the equation that resulted from this study verified the Weber number scaling parameter (consisting essentially of the ratio of inertia to capillary forces) and is very similar to the expression obtained for the time response of a deformed liquid drop.

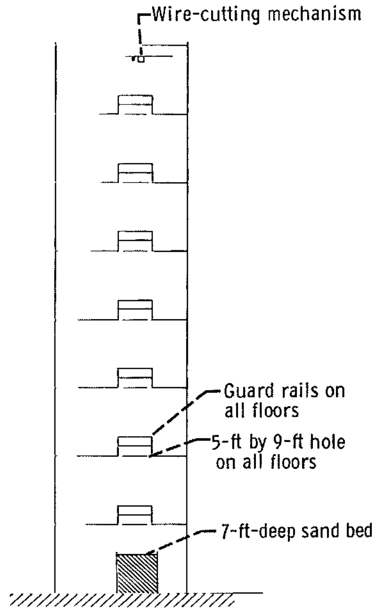
The purpose of this report is to present the results of an experimental investigation of the behavior of the liquid-vapor interface of two cryogenic liquids, nitrogen and hydrogen, when exposed to a weightless environment. The primary objectives of this investigation were the determination of the zero-gravity equilibrium configuration of the liquid-vapor interface and the extension of the Weber number scaling parameter for the time required for the liquid-vapor interface to reach equilibrium to the cryogenic liquids. The study was conducted for spherical and cylindrical experiment tanks in a 2.3-second drop-tower facility.

APPARATUS AND PROCEDURE

Drop-Tower Facility

The experimental results were obtained in the 100-foot zero-gravity, drop-tower facility at the Lewis Research Center. A photograph of the drop tower and a schematic drawing showing pertinent details are presented in figure 1. Initiation of zero gravity

(a) Exterior view.



(b) Schematic drawing.

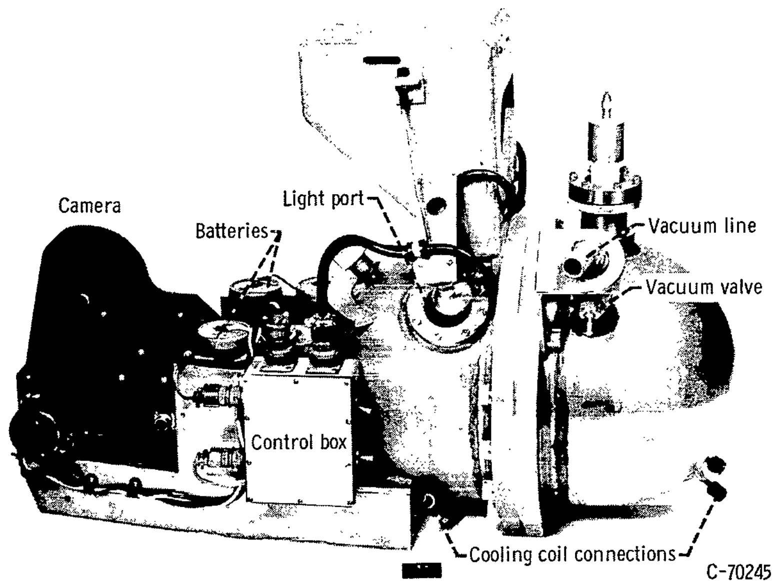
Figure 1. - 100-Foot drop-tower facility.

(free fall) is accomplished by the activation of a compressed-air release mechanism at the roof of the tower that causes the failure of a strand of music wire from which the experiment is supported prior to dropping. Termination of zero gravity occurs when the experiment reaches the first floor of the tower, where it is decelerated in a 7-foot-deep bed of sand. The actual free-fall distance is 85 feet, yielding a 2.25-second period of zero-gravity time. Air drag on the experiment package is kept below 10^{-5} g by allowing the experiment to free fall inside an air drag shield. A more detailed description of the facility is given in references 2 and 3.

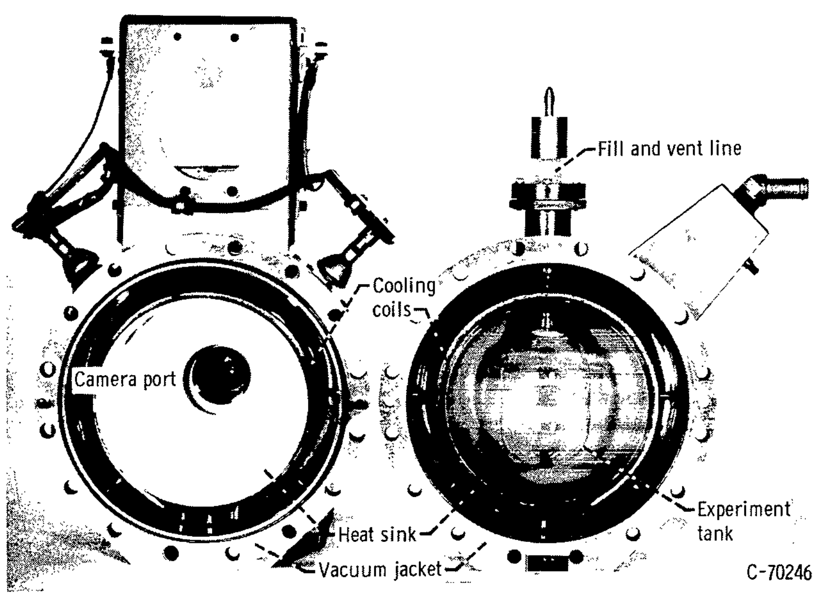
Experiment Package

Photographs of the experiment package used for this investigation are presented in figure 2. This package consists essentially of a 16-millimeter high-speed motion-picture camera and a glass experiment tank, which was suitably mounted and illuminated by two 20-watt light bulbs to allow the behavior of the liquid-vapor interface to be photographed during the free fall. Electric power for the camera and the lights was carried on board the package in the form of rechargeable nickel-cadmium batteries.

Because the liquids under investigation in this study were cryogenic, provisions were made to reduce the heat-transfer rate to the experiment tank so that the liquid state could be maintained for a time sufficient to conduct the experiment and to minimize any



(a) Exterior view.



(b) Interior view.

Figure 2. - Cryogenic experiment package.

effect of heat addition on the behavior of the liquid during free fall. To accomplish this, the experiment tank was mounted in an evacuated container to reduce conductive heat transfer. An aluminum heat sink was mounted between the experiment tank and the vacuum jacket to reduce radiant heat transfer (see fig. 2(b)). The heat sink was operated at liquid-nitrogen temperature for both test liquids investigated. The resulting calculated heat-transfer rate to the experiment tank when filled with liquid hydrogen was less than 1 Btu per hour per square foot. The experiment tank was maintained at atmospheric pressure during this investigation by allowing the fill and vent lines to remain open to the atmosphere.

Experiment Tanks and Test Liquids

Spherical and cylindrical glass tanks were used in this experimental study. The inside diameters of the spherical tanks were 5.8, 7.3, 8.3, 9.8, and 12.4 centimeters. The cylindrical tanks had inside diameters of 5.8 and 8.3 centimeters.

The liquids used were nitrogen and hydrogen. The pertinent physical properties of the test liquids are given in the following table:

Property	Nitrogen	Hydrogen
Temperature at 1 atm, $^{\circ}K$	77.4	20.4
Density, g/cu cm	0.807	0.0710
Surface tension, dynes/cm	8.83	2.16
Purity	(a)	(b)

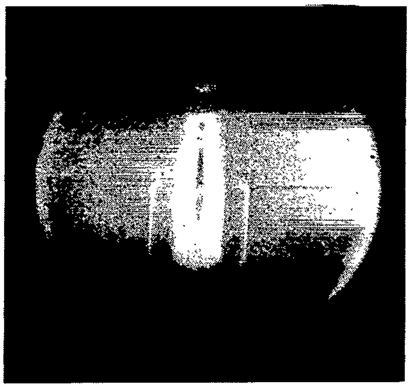
[a]Military specification, P-27401A.

[b]Military specification, P-27201.

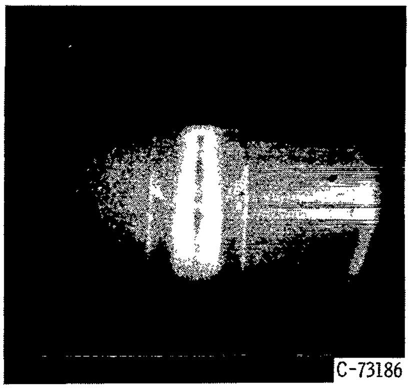
RESULTS AND DISCUSSION

Interface Configuration

An analysis of the motion-picture data obtained during each test drop revealed that the behavior of the liquid-vapor interface of both liquid nitrogen and liquid hydrogen when exposed to a weightless environment appeared to be identical to that previously observed (refs. 2 and 3) for liquids having 0° contact angles with the solid tank walls. Typical photographs taken from the motion-picture data showing the 1-g and zero-gravity interface configurations are presented in figure 3 for liquid nitrogen in a cylindrical tank. In



(a) 1-g interface configuration.



(b) Zero-gravity interface configuration.

Figure 3. - Typical liquid-vapor interface configuration for liquid nitrogen in cylindrical tank.

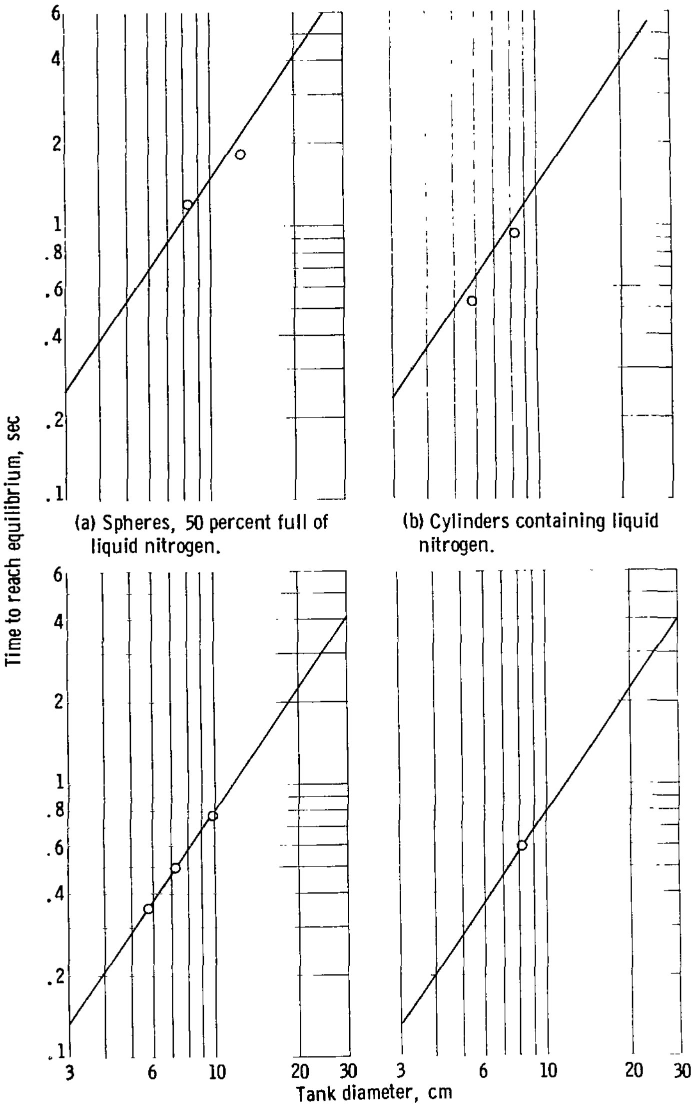
cylindrical tanks, in which only liquid nitrogen was studied, the configuration of the liquid-vapor interface was observed to be a surface of constant curvature having a radius equal to the radius of the cylinder. This configuration of the liquid-vapor interface in cylindrical tanks is the configuration exhibited by liquids having contact angles of 0° (ref. 3). In spherical tanks, both liquids wetted the tank wall completely, as would be predicted for liquids having 0° contact angles (ref. 2). Based upon the similarity of behavior of these cryogenic liquids with liquids of known 0° contact angles (refs. 2 and 3), it is concluded that the contact angle of liquid nitrogen and liquid hydrogen with glass is 0°. Typical photographs showing the liquid-vapor interface in spherical tanks are not presented because the quality of the motion-picture data does not permit photographs suitable for report reproduction.

Time Response

As mentioned previously, the results of the experimental study (ref. 7) established a functional dependence of the time T for the liquid-vapor interface of several common liquids to reach equilibrium on the pertinent liquid parameters and system dimensions for spherical, cylindrical, and annular tanks. The time to reach equilibrium is herein defined as the time for the first pass of an underdamped system through its steady-state position. The form of the equation that resulted from this study verified the Weber number scaling parameter and is

$$T = K\left(\frac{\rho}{\sigma}\right)^{1/2}(D)^{3/2} \tag{1}$$

where K is an empirical constant related to the reciprocal of the square root of the Weber number $(We)^{-1/2}$, ρ is the density of the liquid, σ is the liquid-vapor surface tension, and D is the diameter of the tank. The constant K was found to be a function of the geometry of the system. The time required to reach equilibrium was taken as the time required for a point on the 1-g interface (lying on the vertical centerline of the tank) to traverse the straight-line distance to its perpendicular projection on the zero-



(c) Spheres, 80 percent full of ethanol.

(d) Sphere, 80 percent full of liquid hydrogen.

Figure 4. - Effect of tank size on time to reach equilibrium.

gravity steady-state theoretical interface (see the appendix).

Nitrogen. - The results of the investigation to determine the time required for the liquid-vapor interface to reach its equilibrium configuration are presented in figure 4(a) for spherical tanks and in figure 4(b) for cylindrical tanks. The time to reach equilibrium is plotted as a function of tank diameter in these figures. The curves presented in these figures were determined from equation (1) with values of K of 0.158 and 0.146 for the 50-percent-full spherical tanks and the cylindrical tanks, respectively (see ref. 7).

Close correlation of the data obtained in this investigation for liquid nitrogen in spherical and cylindrical tanks and the curves determined from equation (1) is evident from an examination of figures 4(a) and (b). Therefore, the Weber number scaling parameter for the time required for the liquid-vapor interface to reach equilibrium (reported in ref. 7) is valid for predicting the time response of liquid nitrogen.

Hydrogen. - The investigation of liquid hydrogen was limited to one test drop in a spherical tank. Because the hazards involved in operating with hydrogen dictated a relatively complex filling and venting procedure, the data were obtained for tanks 80 percent full. The investigation of reference 7 that established the value of the empirical constant K to be used in the Weber number scaling parameter was limited to spheres 50 percent full. Therefore, before the results of this investigation could be analyzed, the empirical constant K had to be determined for spherical tanks that were 80 percent full.

A series of drops was made with spheres that ranged in diameter from 5.75 to

9.84 centimeters and were nominally 80 percent full of ethanol. The results of the study of the time to reach equilibrium for the liquid-vapor interface in spheres 80 percent full are presented in figure 4(c). The value of the empirical constant obtained from the curve in figure 4(c) is 0.136.

Presented in figure 4(d) are the data obtained from the investigation of liquid hydrogen in a spherical tank 80 percent full. Also presented in figure 4(d) is a curve determined from equation (1) by using a value of K of 0.136; again good correlation was obtained between the experimental data and the curve that was determined from the Weber number scaling parameter. Therefore, the Weber number scaling parameter for the time required for the liquid-vapor interface to reach equilibrium is valid for predicting the time response of liquid hydrogen.

SUMMARY OF RESULTS

An experimental investigation of the behavior of liquid nitrogen and liquid hydrogen in spherical and cylindrical glass tanks after entering a weightless environment yielded the following results:

1. The configuration of the liquid-vapor interface in spherical tanks for liquid nitrogen and liquid hydrogen is a totally wetted tank wall.

2. The configuration of the liquid-vapor interface of nitrogen in a cylindrical tank is a surface of constant curvature having a radius of curvature equal to the radius of the cylinder.

3. The Weber number criterion, consisting essentially of the ratio of inertia to capillary forces, is valid for predicting the time to reach equilibrium for these cryogenic liquids.

4. The contact angle of liquid nitrogen and liquid hydrogen on glass is 0°.

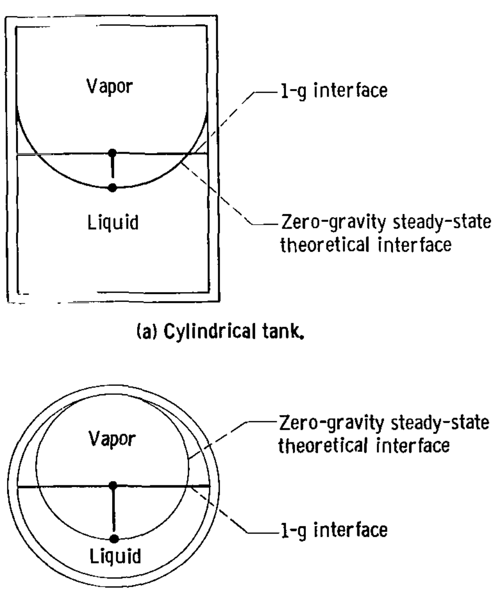
Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 23, 1964.

APPENDIX - DEFINITION OF TIME TO REACH EQUILIBRIUM

The solid-liquid-vapor systems studied in this investigation exhibit characteristics typical of underdamped systems; that is, the liquid-vapor interface oscillates about its steady-state configuration (see ref. 2). Because the zero-gravity test time attainable in the 100-foot drop tower is relatively short (2.25 sec), it is, in general, insufficient to observe the complete decay of the oscillations of the liquid-vapor interface, especially for the larger tank sizes studied. As a result of this limited zero-gravity test time and the oscillations of the liquid-vapor interface, a definition of time to reach equilibrium has been formulated based, in essence, on the first pass of an underdamped system through its steady-state position. Because the zero-gravity configuration of the interface is a function of the shape of the container, the definition of the time to reach equilibrium for each of the tank shapes studied is now given.

Cylinders

Presented in figure 5(a) is the 1-g configuration and the zero-gravity steady-state theoretical configuration of the liquid-vapor interface for a liquid with a 0° contact angle. The time to reach equilibrium was selected to be the time for a point on the 1-g interface (lying on the vertical centerline of the tank) to traverse the straight-line distance to its perpendicular projection on the zero-gravity steady-state theoretical interface. This definition does not imply that the entire liquid-vapor interface be in its zero-gravity steady-state theoretical configuration when this point reaches its specified location on the zero-gravity steady-state theoretical interface.



(b) Spherical tank.

Figure 5. - Schematic drawing of 1-g and zero-gravity steady-state interface configurations for liquid with 0° contact angle.

Spheres

Presented in figure 5(b) is the 1-g configuration and the zero-gravity steady-state theoretical configuration of the liquid-vapor interface for a liquid with a 0° contact angle. The time to reach equilibrium was selected to be the time for a point on the 1-g interface (lying on the vertical centerline of the tank) to traverse the straight-line distance to its perpendicular projection on the zero-gravity steady-state theoretical interface. This definition does not imply that the entire liquid-vapor interface is in its zero-gravity steady-state theoretical configuration (that is, that the liquid completely wets the tank walls) when this point reaches the specified location on the zero-gravity steady-state theoretical interface.

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